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Daylighting control performance of a thin-film ceramic electrochromic window: field study results

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Abstract

Control system development and lighting energy monitoring of ceramic thin-film electrochromic (EC) windows were initiated at the new full-scale Window Systems testbed facility at the Lawrence Berkeley National Laboratory (LBNL) in Berkeley, California. The new facility consists of three identically configured side-by-side private offices with large-area windows that face due south. In one room, an array of EC windows with a center-of-glass visible transmittance (T_v) range of 0.05-0.60 was installed. In the two other rooms, unshaded windows with a T_v=0.50 or 0.15 were used as reference. The same dimmable fluorescent lighting system was used in all three rooms. This study explains the design and commissioning of an integrated EC window-lighting control system and then illustrates its performance in the testbed under clear, partly cloudy, and overcast sky conditions during the equinox period. The performance of an early prototype EC window controller is also analyzed. Lighting energy savings data are presented. Daily lighting energy savings were 44-59% compared to the reference window of T_v=0.15 and 8-23% compared to the reference window of T_v=0.50. The integrated window-lighting control system maintained interior illuminance levels to within ±10% of the setpoint range of 510-700 lux for 89-99% of the day. Further work is planned to refine the control algorithms and monitor cooling load, visual comfort, and human factor impacts of this emerging technology.

Keywords: Building energy-efficiency; Electrochromic windows; Daylighting; Control systems

1. Introduction

Electrochromic (EC) glazings offer dynamic and responsive control of the thermal and optical properties of the building façade. This functionality can be used to maximize occupant comfort and performance while minimizing annual energy use and peak electric demand. They are expected to yield greatest benefits in cooling-load dominated buildings, such as commercial buildings located in temperate and hot climates, in homes in the sunbelt and in parts of the nation where electric load management is of critical concern. EC windows may also be of benefit for offsetting the need for heating in cold climates if controlled to admit solar heat gains.

While electrochromic glazings have been the subject of computer simulation studies for many years it has only been in the last few years that full size products have been evaluated in test rooms or buildings. In 1999, electrochromic residential skylights were tested in outdoor test rooms and showed 50% reductions in cooling loads compared to spectrally selective glazings [1]. In 2000, LBNL completed the first full-scale field demonstration in the U.S. of large-area electrochromic windows in an office building [2]. The project demonstrated that multiple EC windows could be smoothly switched across their dynamic range and could be fully integrated into a complete daylight, glare and energy control system. Although this project reinforced the potential importance and value of this technology, at the same time it highlighted a series of complex interactions that are not well understood by manufacturers, researchers or specifiers. For example, darkening an electrochromic window to control glare and improve visual performance in some

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conditions will increase lighting energy use. These studies showed the potential for electrochromics but underscored the extent to which numerous building integration and systems engineering issues need to be studied and resolved if electrochromic products are to be successful in meeting all market needs. Parallel work in the EU SWIFT program [3] and the International Energy Agency Task 27 [4] is being conducted worldwide.

This multi-year project, supported by the California Energy Commission through its Public Interest Energy Research Program and by the U.S. Department of Energy, is intended to expand and accelerate a wide range of field engineering, demonstration and evaluation studies to help move the electrochromic window technology from the laboratory to products suitable for building applications. This initial study begins to address two key overall challenges that are faced by many new technologies and specifically by complex dynamic systems such as electrochromic (EC) windows:

1) As an actively controllable dynamic system, EC windows face many integration challenges that are not addressed by most conventional window systems. Integration of the dynamic EC window within the building envelope and with other building systems is critical to obtaining a flexible and reliable whole building solution that will meet energy savings, active load management and occupant objectives. Integrated envelope-lighting control algorithms and commissioning and diagnostic tools need to be developed, tested and evaluated to determine the impacts on architectural design, energy performance, occupant acceptance, and reliability.
2) Limited performance data are available to the public, to building owners and to design professionals to understand and assess the overall benefits and risks of this technology in realistic building situations. Controlled full-scale tests demonstrate and validate technology performance, assuring interested parties that the technology works and is consistent with performance claims.

This study demonstrates a first-generation prototype electrochromic window and daylighting control system and quantifies its impact on lighting energy use and peak electric lighting demand in a full-scale office testbed. Assessments of the prototype EC window controller and the integrated EC window-lighting control system performance are given as well. This field test evaluated ceramic thin-film electrochromic devices that were produced in a pilot production facility. The EC windows were controlled continuously over the full switching range (visible transmittance, T_v, range of 0.05-0.60) using an alpha prototype window controller. Control of the EC windows was synchronized with a daylighting control system to maintain a total illuminance level within a setpoint range. The selected control algorithm is one which has been modeled in prior simulation studies [5] to yield optimum total annual energy and peak demand savings in typical U.S. commercial buildings (with an electricity-to-gas fuel ratio of 3:1) compared to conventional window systems. The control algorithm modulates the EC window in real time so that it provides sufficient daylight to reduce or eliminate the use of fluorescent lighting while minimizing solar heat gains. The EC integrated system was compared to two types of unshaded reference windows (T_v=0.50 or 0.15) with the same dimmable fluorescent lighting system. This initial data (space conditioning data will be monitored in future tests) provides guidance for refining the ongoing field test program, helps manufacturers better assess controls integration issues, and provides public stakeholders with timely information on which to base future planning of R&D towards market deployment of commercial products.

2. Background

Field tests provide valuable information that cannot otherwise be obtained from computer simulations or limited bench-scale tests. In the case of EC window operations and daylighting controls, there are several barriers that prevent one from fully understanding whether an emerging technology will actually work and deliver the purported benefits in the real world. EC window switching operations are dependent on the size of the device, temperature of the device, frequency of commands issued to the EC window, and response of the EC controller to these commands. There is typically insufficient spectral data to characterize even the bleached and fully colored properties (let alone intermediate states) of a single-pane EC device at normal incidence and at room temperature so simulation results that rely on such data may not be entirely accurate. Similarly with daylighting control systems, simulation programs typically predict daylight levels at the work surface then compute total energy use from these data. Few programs are able to model the complexities of photoelectric control systems which dim the fluorescent lighting, and these programs are typically not linked to thermal analysis. While simulation programs provide useful insights into trends of overall energy and mechanical system impacts on whole building annual energy use, field tests supplement this information by providing detailed performance information under real sun and sky conditions.

The drawback of conducting field tests early in the product development process is that the technology may not be fully developed, so the performance data may not be completely indicative of the performance expected from a mature product. The electrochromic window systems tested in this study are emerging technologies. The EC window controller is an alpha prototype designed to switch the EC to intermediate states with some limitations that are likely solvable given further engineering R&D. Field tests provide industry with a means of testing, debugging, and iterating on a design prior to its release to the general public. This research pushes the leading edge of R&D beyond a typical manufacturer’s short-term commercialization focus and resources; therefore expectations for product performance must be aligned with this in mind.

Preliminary integrated window-lighting control system and lighting energy performance are presented in this study. Heating and cooling load impacts in addition to lighting energy and control system performance will be monitored in future planned tests. Non-energy issues were partially addressed in an earlier LBNL EC field study and will continue to be evaluated with both monitored data and a detailed human factors study using subjective surveys.

3. Method

3.1. Facility description

A new window systems testbed facility was built at LBNL, Berkeley, California (latitude 37°4’N, longitude 122°1’W) in Summer 2003. The facility was designed to evaluate the difference in thermal, daylighting, and control system performance between various façade, lighting, and potentially mechanical systems, as well as to conduct human factors studies. The facility consists of three identical side-by-side test rooms built with nearly identical building materials to imitate a commercial office environment (Figure 1). Each test room is 3.05 m wide by 4.57 m deep by 3.35 m high and has a 3.05 m wide by 3.35 m tall reconfigurable window wall facing due south. The windows in each test room were minimally obstructed. Exterior obstructions had altitude angles that are less than 20° for azimuthal angles from 90-140° (0°=north) and less than 8° for azimuthal angles from 240-270°. Interior surface reflectances of the floor, walls, and ceiling were 0.18, 0.85, and 0.86, respectively. The rooms were unfurnished at the time of these tests. At the time of the test, a packaged air conditioner provided space conditioning to the corridor outside the test rooms and partially to the test room interiors. Dedicated test room space conditioning had not yet been made operational. Therefore over the course of this test period, interior air temperatures in the test rooms ranged from 28-38°C over the course of the day. The sections below explain how systems and monitored data were influenced by these conditions.

Fig. 1. Exterior and interior view of the test facility. In the exterior view, Room C is to the west (left), Room B is in the center, and Room A is to the east (right). The test rooms were unfurnished for the data given in this report.

EC windows from a prior LBNL field test were used as reference windows for this study. The window wall consisted of an array of four upper (62.1 x 43.2 cm) and four lower (62.1 x 172.6 cm) EC windows. The maximum vision window head height was 2.80 m. In each room, all EC windows were set to a constant transmittance level of either T_v=0.15 or T_v=0.50 throughout the day. Use of these EC windows facilitated rotation of the two reference cases between the two end rooms over the monitored period thus reducing measurement uncertainty due to differences in daylight availability and view across the full façade of the test facility. The EC windows could be set to T_v=0.50 and T_v=0.15 in Rooms A and C, respectively, then switched to Rooms C and A on another day. This setup also facilitated an evaluation of the measurement error when Rooms A and C were set to the same transmittance level (see Section 3.5). It was originally intended to use these EC windows also in the dynamic mode, but the automated control interface did not function properly so the manual keypad supplied with the windows was used instead. Neither the windows nor the electronic controllers were unduly influenced by the interior air temperature. Tests conducted after the rooms were conditioned showed no significant change in the EC's static operation.

Prototype ceramic, thin-film electrochromic windows (Tv=0.05-0.60) were used as the test case in Room B. Reference to an electrochromic window in the remainder of the paper will be to these devices. Fifteen ~43 x 85 cm electrochromic units were used to form this window wall. The vision and framing areas were matched to the reference rooms as closely as possible (given size availability from the manufacturer). The maximum vision window head height was 2.77 m. Custom thermally-broken aluminum frames were built to hold all insulating glass units (IGU) within the window rough opening. Comparative reference and test case window wall data are given in Table 1. An "alpha" prototype window controller, provided by the manufacturer, was used to switch the electrochromic windows. This controller was designed to provide the following capabilities:

1) full continuous modulation between T_v=0.05-0.50 and 0.60 (the alpha controller had a limitation of a deadband control range where a requested or commanded value, $T_{v\ cmd}$, between $T_{v\ cmd}$=0.50-0.60 resulted in the EC being fully bleached to T_v=0.60),
2) the actual EC window T_v will match the requested value to within 10% of the requested value once the EC has completed switching,
3) the controller will not adjust the window if $T_{v\ cmd}$ is within ±0.02 of the current T_v, and
4) depending on the temperature of the electrochromic, the depth of switching requested, and the direction of switching (bleached to colored or colored to bleached), the window will switch within 1-5 min.

Similar to the reference cases, neither the windows nor the electronic controllers were unduly influenced by the interior air temperature. Tests conducted after the rooms were conditioned showed no significant change in dynamic EC operations.

Table 1
Comparative between-room window data

	Vision Area (m^2)	% delta from B	Frame Area (m^2)	% delta from B	Spandrel Area (m^2)	Total Area (m^2)
Room A	4.91	-11%	2.51	-11%	2.14	9.56
Room B	5.50	0%	2.81	0%	1.26	9.56
Room C	4.91	-11%	2.51	-11%	2.14	9.56

Two 0.61x1.22-m pendant, indirect-direct (~95%, 5%) fixtures (LiteControl Classica P-I-5544T8-CWM) with four T8 (25-mm) 32-W fluorescent lamps (Phillips Advantage Universal Start F32T8 ADV841/ ALTO 4100°K, CRI=86), continuous dimmable electronic ballasts (OSRAM Helios QTP2x32T8/120 DIM5-B), and a shielded photosensor (Perkin Elmer VTB1012B, 0.02% per °C) were used in each room (Figure 2). The two fixtures were placed along the centerline of the window with the south ends of the first and second fixture located 0.60 m and 2.74 m from the window wall, respectively. The fixtures were suspended 0.76 m from the ceiling. The photosensor was placed at the south end of the second light fixture, 2.73 m from the window wall and flush with the bottom of the fixture, 2.54 m above the finished floor. The photosensor had a 60° cone of view and was pointed downward, normal to the floor. Its view was defined by a circular area on the floor with a radius of 1.47 m. The ballasts produced

0% light output for a minimum power input of 9.4%. Lamp efficacy is affected by air temperature. Section 3.4 below explains how monitoring lighting energy use was corrected for changes in lamp efficacy.

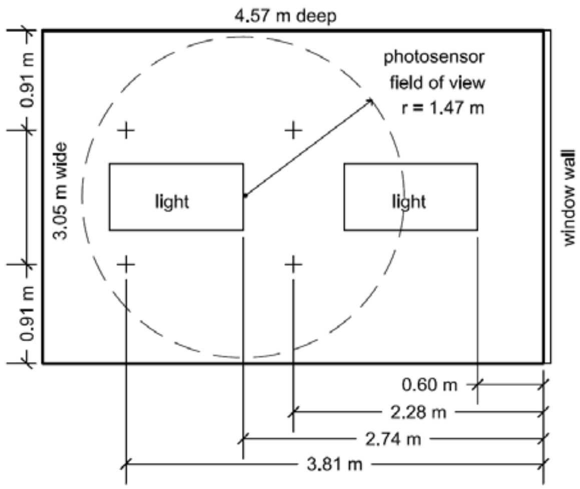


Fig. 2. Plan view of a test room showing position of the lighting fixtures, photosensor and its field of view, and interior work plane illuminance sensors (+ symbol).

3.2. Tested configurations

3.2.1. Reference cases

Two reference case configurations in either Rooms A or C were defined with static unshaded windows, either T_v=0.50 or T_v=0.15, as described above. These cases will be referred to in the text as "50%-window" and "15%-window". The dimmable electric lighting system was automatically controlled every 30 s to supplement available daylight so as to maintain a minimum horizontal work plane illuminance of 510 lux within the rear zone of the test space. If there was sufficient daylight, the lights were turned off; fluorescent illuminance was 0 lux and power usage was 24.5 W or 9.4% of full power. The rear zone was defined by the photosensor's field of view. The photosensor's unconditioned voltage signal was processed via LBNL software and used to control the ballast. Dimming levels were determined using closed-loop proportional control.

3.2.2. Test case

The test case configuration in Room B was defined with a dynamic electrochromic window and the same dimmable daylighting controls as the reference case. The transmittance of the electrochromic window was automatically adjusted if necessary every 1 min to provide an average work plane daylight illuminance of 540-700 lux within the rear zone of the test space. The LBNL supervisory control system was implemented using National Instruments LabVIEW software and interfaced with the manufacturer's EC window controller. Proper switching of the window was accomplished using closed-loop proportional control via the ceiling-mounted photosensor. The transmittance sensors described in the next section were not used for control.

3.3. Monitored data

Weather data were sampled and recorded every 1 min. All exterior illuminance levels were monitored using a color- and cosine-corrected silicone diode photometric sensor (LI-COR LI-210SA, ±1.5% to 150 klux). Global horizontal exterior illuminance was monitored on the roof of the testbed building, which was minimally obstructed. Global vertical illuminance was measured on the south façade just above the center of Room B's window. Outdoor drybulb temperature was measured using a shielded thermistor (YSI 44016, ±0.2°C). Interior air temperatures at 10 locations in each test room were measured using shielded and unshielded thermistors of the same type.

Lighting energy data were sampled every 1 s then averaged and recorded every 1 min. Lighting energy use was monitored for each test room using a watt transducer (Ohio Semitronics GW5, ±0.2% of reading).

Interior illuminance data were sampled and recorded every 1 min. All interior illuminance levels were monitored using the same type of photometric sensor as the exterior sensors (LI-COR LI-210SA, ±1.5% to 7500 lux, ±0.15% per °C maximum within operating temperatures between –20°C to 65°C).

Relative, not absolute, visible transmittance, of each of the electrochromic double-pane windows was sampled and recorded every 1 min in order to check control system operations. Measuring absolute visible transmittance of an insulating glass unit (IGU) in the field is non-trivial particularly if one wants to monitor many window units accurately at a reasonable cost. Instead, a visible transmittance sensor was devised. The sensor was composed of a paired white LED emitter (Chicago Miniature Lighting, Inc. CMD333UWC, peak wavelength is 475 nm; peak of the photopic spectrum is 550 nm) mounted on the exterior surface and a shielded photodiode detector (Perkin Elmer VTB1012B, 330-720 nm) mounted on the opposing interior surface. Each of the 15 test case EC IGUs were fitted with a paired emitter-detector sensor located at the same location normal to the face of the IGUs: 7.6 cm from the side edge and 30.5 cm from the bottom edge. Maximum sensor output voltage was correlated to the bleached EC transmittance value provided by the manufacturer (T_v=0.60, normal incidence) after the EC windows had been switched to this level for 1 h. The surface temperature of the windows at the time of the correlation was approximately 25°C. The visual appearance of the EC window wall at this state was well matched and uniform. For the sensor output voltage of zero, T_v was set to zero. No corrections were made to the monitored data to account for the variation in sensor output signal with temperature, however 1) the detector, which is more sensitive to temperature, was placed in the interior rather than outdoors and 2) all detectors were exposed to the same temperature conditions (e.g., due to solar radiation, etc.) so their relative response was expected to be similar. After the completion of this study, the test rooms were space conditioned. A test was then conducted to determine the temperature sensitivity of the sensors. At 42°C, T_v was found to be 0.05-1.0 lower in value compared to the 21°C condition. Bench-scale measurements were used to evaluate the relative accuracy of the sensors to reference static materials (Table 2). There was very good to moderate agreement with the manufacturer's reported T_v value for the various window samples.

Table 2
Center of glass visible transmittance (Tv)

	Stated Value	Measured Value	Percent Difference
Clear single pane glass (5 mm)	0.90	0.94	-4%
Clear double pane glass (3 mm)	0.81	0.83	-2%
Grey double pane glass (6 mm)	0.12	0.12	0%
50% grey film	0.50	0.50	0%
35% grey film	0.35	0.36	-3%
5% grey film	0.05	0.06	-20%
Room B EC window colored	0.05	0.08	-60%
Room B EC window bleached	0.60	0.62	-3%

The LBNL supervisory control system issued a T_v command to adjust the dynamic EC windows. These data are reported in the Figures as "$T_{v\ cmd}$". This command was given within the range of $T_{v\ cmd}$ =0.05-0.60. As noted above, the alpha EC window controller has a deadband control range where a requested value between $T_{v\ cmd}$ =0.50-0.60 resulted in the EC simply being fully bleached to 0.60.

Within the insulating glass unit, the EC coating is on the outboard glass layer and on the inboard surface (#2). Since the EC coating works by absorption, the exterior glazing is expected to become hot at low transmittance states. The temperature of the EC windows was determined using an unshielded thermistor (YSI 44016, ±0.2°C) mounted with silicone on the exterior surface of the window. In Room B, measurements were made at a distance of 30.5 cm in from the side edge and 15.2 cm from the lower edge of the IGU and on the lower, middle, and highest window in the center column of the window wall. This measurement was affected by incident radiation. There is controversy over which of several methods is best for obtaining an accurate surface temperature reading and this solution was considered to be a good compromise between the various known methods.

3.4. Data analysis methods

Data analysis consisted of evaluating the prototype EC window controller, the EC window and lighting control system performance, and quantifying lighting energy savings. Data were collected from July 25, 2003 to September 14, 2003 from 5:00-19:00 (14 h) using the LabView National Instruments data acquisition software (after this period, the windows and rooms were reconfigured). All data are given in Standard Time. The window and lighting control system was commissioned, tested and developed iteratively over this period to refine the algorithms and hardware operations according to observations in the field. Several basic filters were placed on the monitored data to eliminate data when there was an interruption in conditions due to occupants in the room. Additional filters were used to eliminate data when the EC window or lighting system was not operating as intended.

For the purposes of energy-efficient control and uniform façade appearance, an ideal EC window controller would have the following characteristics at all times irrespective of EC operating temperature (-30°C to +90°C), window size, or partial shading across a window (part in sun and part in shadow):

1) Ability to achieve visual uniformity across each device as it is switching (within-pane uniformity). This is to avoid the iris effect seen in early EC devices when a non-uniform potential was established across the surfaces of the transparent conducting layers and the areas nearest the bus bars colored faster than the center portion of the window.
2) Ability to switch an EC window to a specified transmittance level. The transmittance level is defined as any continuously modulated level between the bleached and colored states. This enables accurate and optimal control so as to achieve control objectives with minimal hysteresis.
3) Ability to achieve visual uniformity between multiple EC windows at all times irrespective of whether the devices are in transition (while switching) or at rest (completed switching). This is to avoid a checkerboard façade appearance (between-pane uniformity or multipane synchronization).
4) Ability to report accurate center-of-glass T_v data. For closed-loop control and for window systems that take a long time to switch, knowing the state of the EC window can help to avoid control hysteresis under variable conditions (e.g., partly cloudy skies).
5) Ability to maintain the EC window at a stable transmittance state for a sustained period. There should be minimal change in value (<5% of value) over several days. If a supervisory command must be issued to maintain a given state, the frequency of such commands must be specified. This enables the supervisory controller to distinguish between transitional and at-rest EC states and between changes in exterior conditions and EC window transmittance status.
6) If there is a reduction in the EC switching range over extended cycling, the controller should be able to maintain the above performance characteristics.
7) There are numerous interface specifications between the EC window controller and the supervisory controller that are not detailed here. An example of this is the ability of the EC window controller to respond immediately to the supervisory controller with signal acknowledgment and status information.

This analysis focused on systematically evaluating aspects of characteristics 2-3 above using monitored field test data. The remaining characteristics were evaluated based on observations (1) or were not evaluated because controlled laboratory tests could provide a more accurate assessment (4-7). Methods to evaluate these characteristics have not been defined in prior research and are therefore evolving based on observations and improvements in method. In this analysis, given the early development stage of this alpha prototype controller, automatic control of the array of EC windows was considered successful if:

1) the EC windows responded promptly at all times without error and all IGU transmittances matched the transmittance level requested by the supervisory control system ($T_{v\ cmd}$) to within ±10% of value when either at rest or in transition (i.e., in the process of switching to another state) over the 14-h day, and
2) such control was achieved over the range of operating temperatures monitored throughout the test period.

If the transmittance of side-by-side EC windows were matched to less than ~10% difference between windows, the visual appearance of the window wall was fairly uniform and closely matched. As the transmittance of side-by-side windows differed by greater than ~10%, the visual appearance of the window wall became more noticeably non-uniform. The transmittance sensors were placed at the same relative position to the EC device bus bars on all IGUs to ensure an equitable evaluation.

The EC window and lighting control system performance was evaluated by determining if the average total rear zone work plane illuminance was within ±10% of the 510-700 lux range (459-770 lux) for 90% of the 14-h day. The average total rear zone work plane illuminance, Iwkpl, was defined as the average illuminance measured by four illuminance sensors located 2.28 m and 3.81 m from the window wall, 0.91 m from either side wall, and at a height of 0.76 m (see Figure 2). The total included both the daylight and fluorescent lighting contributions to the work plane illuminance. If the total illuminance was not maintained above the minimum setpoint level (-10% of 510 lux), lighting was considered to be inadequate for visual tasks. If the total illuminance exceeded the maximum setpoint level (+10% of 700 lux), the added solar heat gains could increase cooling loads and decrease total energy-efficiency. Fluorescent lighting illuminance levels were computed using a correlation of work plane illuminance to fluorescent lighting power consumption (see Section 3.5.2) for each of the three test rooms to diagnose and illustrate control system performance.

Lighting energy use was affected by interior temperature conditions. Fluorescent lamps are relatively sensitive to ambient temperature because they are low pressure lamps. After the completion of this study, the test rooms were space conditioned. A test was then conducted to determine the correlation of lighting energy use and interior illuminance to air temperature measured at three locations near the lighting fixtures. The efficacy of the lamps was increased slightly as temperatures increased. To produce the same illuminance, the lighting system required 7 W maximum more power at 21°C than at 38°C. Corrections were made to the lighting energy use data based on these correlations, resulting in a 2-5% reduction in percentage daily lighting energy savings. Daily lighting energy use was computed for the 12-h period from 6:00-18:00. Sunrise during the monitored period was typically at 5:30 and sunset was at 18:30. Daily lighting energy use based on occupancy was also computed for this 12-h period where ASHRAE 90.1-1989 lighting load schedules [6] were applied to the lighting power use (Table 3). The lighting load schedule reflects typical office lighting use in commercial buildings over a weekday where either manual switching or occupancy sensors reduce the total lighting load. These hourly factors were multiplied by the 1-min lighting energy use data (0:00-0:59 for each hour) then summed to arrive at daily lighting energy use for an occupied perimeter office zone. Daily lighting energy use savings were computed for the reference cases with and without daylighting controls. Without daylighting controls, daily lighting energy use was 180.4 Wh/m^2-floor or 133.7 Wh/m^2-floor with the occupancy schedule.

Lighting peak demand was defined by the average demand between 12:00-13:00 without the occupancy schedule. For the south perimeter zone in typical commercial buildings, total building peak demand often occurs at or after the noon hour (depending on the thermal mass of the building) when solar gains are at maximum levels. Peak lighting demand reductions can be used to offset increased cooling loads. Peak demand savings were computed for the reference cases with and without daylighting controls. Without daylighting controls, the peak lighting demand was 14.9 W/m^2 (1.39 W/ft^2).

Table 3
ASHRAE 90.1-1989 lighting weekday schedule

Hour of day	Percent of full lighting load
6:00-7:00	10%
7:00-8:00	30%
8:00-12:00	90%
12:00-13:00	80%
13:00-17:00	50%
17:00-18:00	30%

3.5. Error analysis

Lighting energy savings were defined as:

Energy savings = Reference case energy use – Test case energy use ± Adjustments (1)

"Adjustments" bring energy use quantities measured in each room to the same set of reference conditions and are typically derived from physical facts. There were several aspects that contribute to potential error in between-room energy comparisons: a) the position of each room differed, b) the glass and framing layout of the reference case windows differed from the test window, and c) the power consumption of the daylighting control systems differed between rooms. No adjustments were needed as explained below.

3.5.1. Difference in average rear zone work plane illuminance due to test room position

The testbed facility was sited with minimal exterior obstructions so as to eliminate as much as possible the positional differences in monitored data between the test rooms. The locations of the two reference case window types were also alternated between Rooms A and C. Adjustments were not made to eliminate the between-room differences in interior daylight levels due to differences in framing and window layout (Table 1). These adjustments cannot be reliably determined because the variations in interior illuminance as a function of solar position, sky condition, reflections off window framing members, and other factors are too complex to predict.

To better understand the impact of room position on between-room comparability, daytime tests were conducted where the windows in Rooms A and C were set to the same level of transmittance and the electric lighting was turned off. These rooms' windows and framing system were identically configured and represent the full range of incident solar conditions across the full width of the testbed facility's south façade. The average rear zone work plane illuminance is shown in Figure 3 for clear sky conditions with the reference case windows set to either T_v=0.50 or T_v=0.15. For the 0-510 lux range when fluorescent dimming occurred, the daily average daylight illuminance level in Room A (east room) was 3.5±22.6 lux (T_v=0.50) and 9.9±9.1 lux (T_v=0.15) greater than Room C (west room) under clear sky conditions. This additional illuminance would cause less than a 1% difference in daily lighting energy use assuming an average difference of 10 lux between rooms.

3.5.2. Lighting power use between test rooms

The amount of power required to produce the same fluorescent lighting illuminance at the work plane may differ between test rooms. To quantify these differences, nighttime tests were conducted after the initial 100 h burn-in of the lamps. The windows were set to a low T_v to block as much night light as possible. Additional measurements were made to determine the contribution of night light to the measurements. The lamps were allowed to warm up at full power for at least 30 min. Power was then stepped down at 5-10% intervals and the lamps were allowed to achieve equilibrium before the next step was made.

The relationship between power consumption and work plane illuminance is shown in Figure 4. Differences in lighting power consumption between all test rooms were no greater than 1.1 W if the average work plane illuminance was between 100-550 lux. Differences were more difficult to characterize for light levels less than 100 lux but these differences were still small (<1 W). This was within the measurement accuracy of the watt transducers (0.2% of reading).

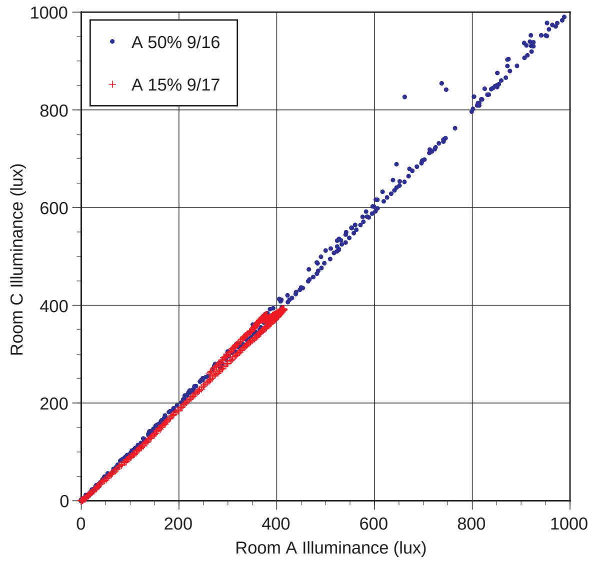


Fig. 3. Correlation between average rear zone work plane illuminance (lux) in Rooms A and C, September 16, 2003, clear sky conditions, with EC windows in both rooms set to either T_v=0.50 or T_v=0.15, daylight only.

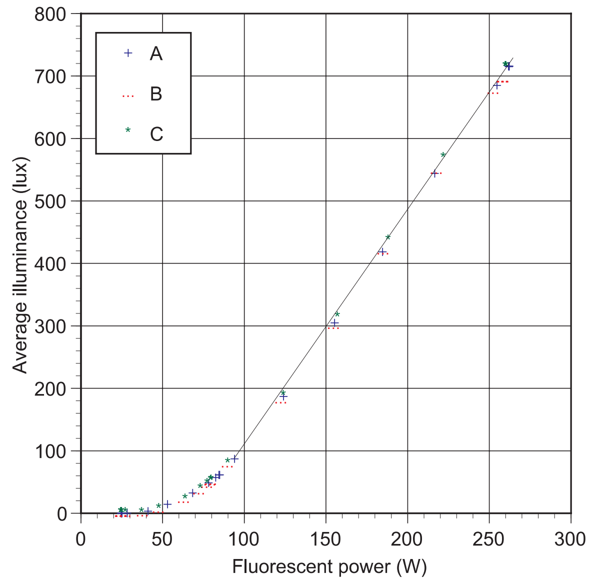


Fig. 4. Correlation between fluorescent power (W) and average rear zone work plane illuminance (lux), electric lighting only for Rooms A, B and C

4. Test results

4.1. Daylighting control system commissioning

Electrochromic windows produce a noticeable shift in the transmitted spectra of daylight as they switch from a clear to a deep blue tinted state. The ceiling-mounted photodiode has a photopically-weighted response with a fairly broad response (330-720 nm, peak 580 nm) compared to the photopic response of the human eye. To verify that the window spectra did not unduly shift the response of the photosensor and therefore cause improper dimming of the electric lighting system, daytime tests were made with the electrochromic set at various fixed levels of transmittance and the fluorescent lighting turned off. The shielded photosensor was set back into the room so that its response was not influenced unduly by the brightness of the window or ground plane. Its field of view, effectively a cone of 60°, was also broad enough to not be overly sensitive to small localized changes in luminance within its field of view. The work plane illuminance was monitored with Li-Cor photometers that have a spectral response corresponding to the photopic response of the human eye; measurement error should be very small (<5% for most light sources).

The correlation between photosensor response to average daylight work plane illuminance for clear sky and foggy days can be seen in Figure 5. Conventional daylighting controls embed a linear correlation of photosensor response to work plane illuminance levels in the control algorithm. The installer can typically adjust the photosensor and indirectly affect the gain or slope of this linear correlation. The results indicate that the varying sun and sky conditions may be a greater source of control error than the spectral shift produced by the EC windows. With the EC held at a constant state, significant scatter occurred within a given day. This scatter was sufficiently broad to encompass the range of scatter that occurred from different EC window transmittance levels. For example, significant scatter occurred on foggy days August 19 and 20 when the EC windows were set to T_v=0.40 in Room B. The scatter on August 8 with the EC windows set to T_v=0.30 was minimal for this clear day and its upper edge coincided with the August 20 upper edge of data (between photosensor signal values of 0.30-0.35 V). The scatter defined by the September 16 data with the EC set to T_v=0.60 overlaps the scatter of August 19-20 across the entire photosensor signal range. With the EC at T_v=0.05, the illuminance levels were too low to allow extrapolation of a linear fit to the entire dimming range. The same observations can be made for Room C.

For Room A, the correlation for September 16 differs significantly from that of August but this difference is not adequately explained by the EC spectral shift alone. While not entirely conclusive given the limited dataset, this preliminary data seems to indicate that the shift in daylight spectra due to the EC window may not be of concern for conventional daylighting controls.

To commission the system for control, the slope of the fit used for controlling the EC window and lighting system was set toward the lower range of the scatter so as to meet the work plane illuminance level for the majority of the day yet still allow for lighting energy savings. Note that using a less conservative fit would result in greater lighting energy savings, but may compromise user satisfaction. For practical applications, the time allotted to manually commission a single perimeter zone is typically no more than 15 min. The procedures used in this study are not for practical applications. The variability of photosensor response to EC spectra under different sun and sky conditions deserves further study to ensure that reliable control operations occur despite the limited time allotted to calibrate the system in practical applications.

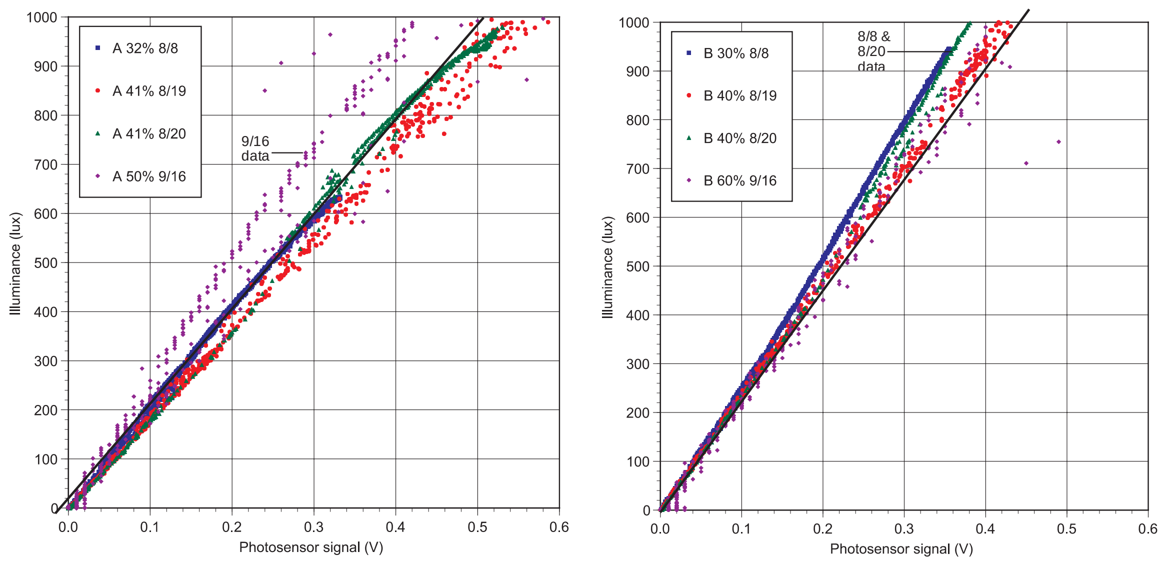


Fig. 5. Correlation between photosensor signal (V) and average rear zone work plane illuminance (lux), daylight only, Room A (left) and Room B (right). August 8 and September 16 were sunny days and August 19-20 were partly cloudy, foggy days.

4.2. Electrochromic window controller performance

For the monitored period, the median transmittance of 15 EC windows was within 10% of the requested transmittance for 60-89% of the 14-hour day (Table 4). When there was a difference greater than 10%, the average deviation was within 14-20% of the requested value. A comparison between the median transmittance of 15 EC windows monitored by the transmittance sensors and the requested transmittance (command value from the supervisory window-lighting control system) is given for a clear day (Figure 6b) and a partly cloudy day (Figure 7b). Note that when the requested value was between $T_{v\ cmd}$ =0.50-0.60, the EC was controlled to T_v=0.60 as dictated by the alpha controller. These deviations were not included in the analysis. Small glitches in an otherwise uniform transmittance command value were typically the result of electronic noise from the photosensor.

Due to the frequent changes in the requested transmittance, the EC windows were seldom allowed to reach a steady state during transitional sun conditions. For example in Figure 6b, the EC was continuously modulated every 1-10 min by the control system from sunrise to 10:30 h and then from 14:45 h to sunset. For this type of device and size, the EC window takes ~1-5 min to attain a steady state transmittance depending on the direction of switching (bleached to colored is typically slower than colored to bleach), depth of switching, and temperature of the device (daytime outdoor drybulb temperatures varied between 13-32°C and the average EC surface temperatures varied between 14-63°C over the monitored period). As a result, the difference between the requested and actual transmittance of the windows varied, particularly during the afternoon hours when the EC switched from colored back to bleached. Another cause for differences between the requested and median transmittance was that the EC controller tended to exhibit hysteresis by over- or undershooting the requested value for the first 1-2 min then settling to the final value in the following 2-5 min. For the hours surrounding noon, the EC windows were allowed to reach a steady state transmittance for 20-30 min with small adjustments of no more than $T_{v\ cmd}$ =0.05. During this period, the constant level of deviation from the requested transmittance level may be due to the limited accuracy of the alpha EC window controller.

From field observations, the EC window wall appeared to be uniform and well matched when at rest. During transition, between-pane uniformity was observed to be moderately acceptable throughout the test period; no single IGU lagged other IGUs during the switching process, for example, and all IGUs appeared to reach the same state of transmittance at the same time. Subtle changes in uniformity within each IGU could be noted if one was closely observing the windows and the background had little visual content (sky view as opposed to view of the trees for example).

Table 4
EC window control system performance

Date	Sky Condition	% of day Tv.diff >10%	Avg Tv.diff when Tv.diff>10%
8/30/2003	Partly cloudy	13%	18% ± 7%
8/31/2003	~Clear	20%	15% ± 5%
9/1/2003	Clear	13%	14% ± 5%
9/2/2003	~Clear	14%	15% ± 5%
9/9/2003	Cloudy	11%	20% ± 8%
9/11/2003	Clear	34%	14% ± 4%
9/14/2003	Partly cloudy	40%	16% ± 5%

$T_{v\ diff}$ is defined as the percentage difference between $T_{v\ cmd}$ and the median T_v value of the 15 EC windows.

4.3. Electrochromic window-lighting control system performance

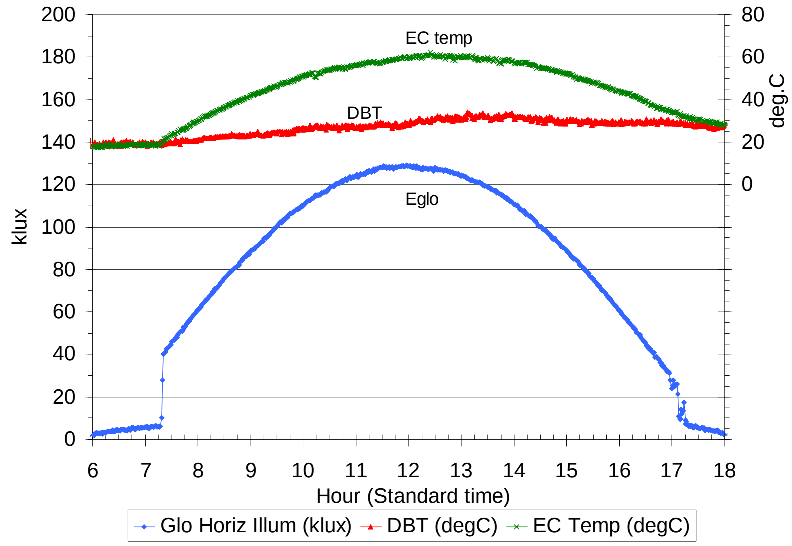
In the test case Room B, the supervisory EC window-lighting system was able to maintain the average rear zone work plane illuminance to within ±10% of the 510-700 lux range (459-770 lux) for 89-99% of the 14-h day. Statistics for individual days are given in Table 5. An example of the performance of the EC window-lighting control system is shown in Figure 6c. Under some conditions, the total work plane illuminance exceeded the bounds of 510-700 lux even though the EC window responded according to the command.

These deviations were due primarily to the photosensor linear correlations that were used to predict daylight work plane illuminance levels. Direct sun was not incident on the work plane illuminance sensors for this time of the year. The EC window-lighting control system also caused the illuminance control boundaries to be exceeded, particularly under variable sky conditions. The pattern of illuminance exhibited a sawtooth pattern as the total illuminance level was allowed to reach the upper or lower bounds of the design range before an adjustment was made to the EC windows (e.g., from 13:30-16:15 on September 11, 2003). While this is unlikely to be perceived by the occupant, this control range can be narrowed to smooth out the data and possibly improve cooling load control. The electric light dimmed smoothly in proportion to available daylight, as expected. The electric lights were allowed to shut off, where light output was zero but power draw was 9.4% of full power.

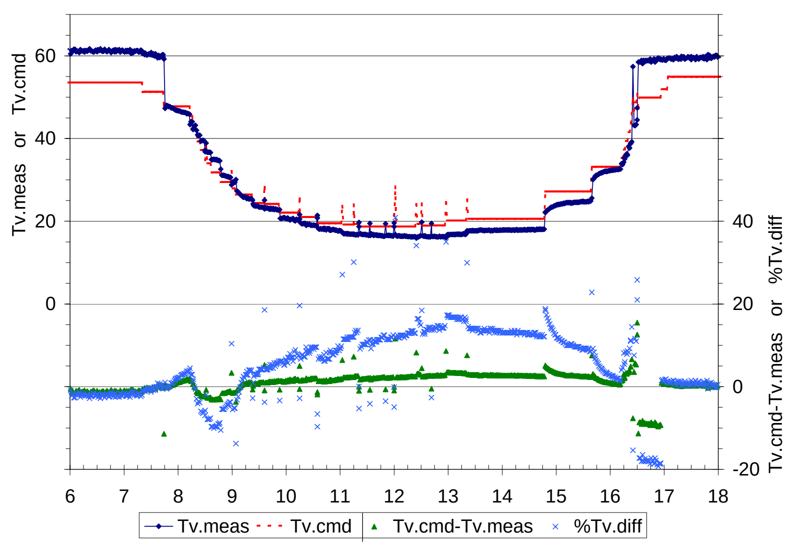
Comparable data are given for the reference case rooms. Note that with the 50%-window, the 700 lux threshold was routinely exceeded 45-63% of the day on partly cloudy (Figure 7c) to clear sunny days as would be expected with large-area windows. In occupied buildings, shades would probably be used to control direct sun and glare. Also note in Table 5 that for the periods when the illuminance was less than 510 lux, the average work plane illuminance level in Room C was on the low end (i.e., 456 and 468 lux) compared to the other test rooms on September 11 and 14 for a significant percentage of the day. This is also illustrated in Figure 6c. Daily lighting energy use savings will be understated for these cases. This problem with the daylighting control system (namely the daylight correlations) will be corrected in future tests.

Fig. 6. Clear sky, September 11, 2003.

(a) Exterior horizontal global illuminance Eglo (klux), outdoor dry-bulb temperature DBT (ºC), and EC surface temperature (ºC).



(b) Median monitored visible transmittance of 15 EC windows ($T_{v\ meas}$), requested T_v set by the LBNL control system ($T_{v.cmd}$), difference in T_v between the measured and command value, and percentage difference between the measured and command value.



(c) Average rear zone work plane illuminance (lux) in Rooms A (T_v=0.50), B (EC) and C (T_v=0.15). Total illuminance (daylight + fluorescent) and fluorescent lighting illuminance data are shown.

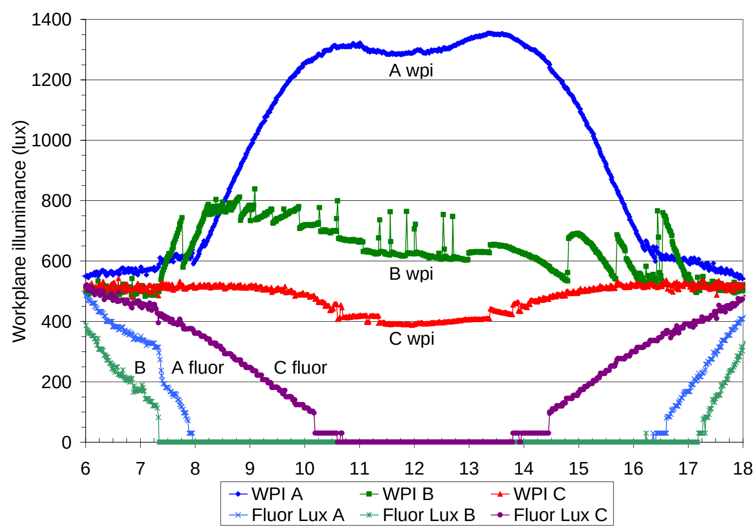
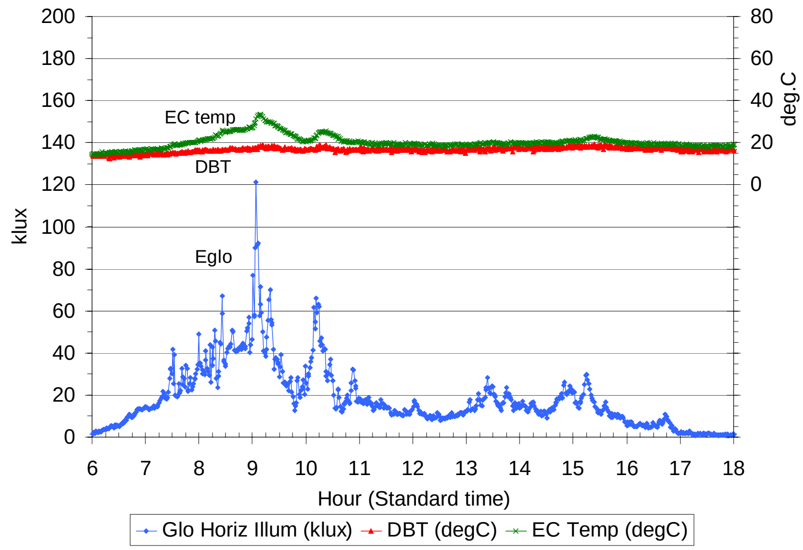
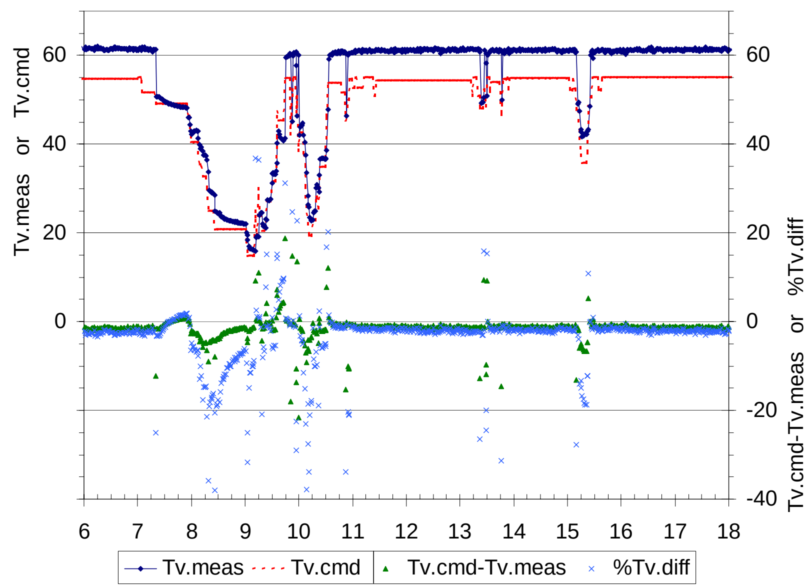


Fig. 7. Partly cloudy sky, September 9, 2003.

(a) Exterior horizontal global illuminance Eglo (klux), outdoor dry-bulb temperature DBT (ºC), and EC surface temperature (ºC).



(b) Median monitored visible transmittance of 15 EC windows ($T_{v\ meas}$), requested T_v set by the LBNL control system ($T_{v\ cmd}$), difference in T_v between the measured and command value, and percentage difference between the measured and command value.



(c) Average rear zone work plane illuminance (lux) in Rooms A (T_v=0.50), B (EC) and C (T_v=0.15). Total illuminance (daylight + fluorescent) and fluorescent lighting illuminance data are shown.

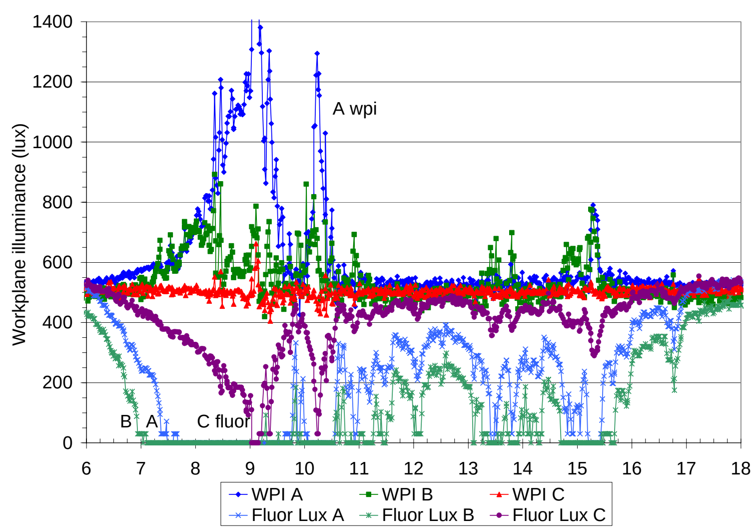


Table 5
EC window-lighting control system performance

Date	% of day WPI>700 lux*			% of day WPI<510 lux**			% of day WPI within 10% of range				WPI avg when WPI>700 lux	WPI avg when WPI <510 lux		
Tv:	0.15	EC	0.50	0.15	EC	0.50	0.15	EC	0.50		EC	0.15	EC	0.50
Room:	A	B	C	A	B	C	A	B	C		B	A	B	C
8/30/2003	0%	5%	45%	30%	36%	17%	91%	99%	57%	avg	727	474	489	501
										sd	21	27	11	8
8/31/2003	0%	23%	62%	30%	24%	8%	99%	98%	41%	avg	731	480	491	504
										sd	33	14	11	5
9/1/2003	0%	33%	57%	30%	20%	2%	88%	93%	46%	avg	745	469	495	502
										sd	33	21	11	8
9/2/2003	0%	28%	63%	27%	25%	9%	97%	97%	40%	avg	739	480	489	503
										sd	30	19	11	7
Room:	C	B	A	C	B	A	C	B	A			C	B	A
9/9/2003	0%	4%	15%	69%	61%	6%	98%	96%	87%	avg	739	497	487	495
										sd	49	13	14	16
9/11/2003	0%	19%	55%	55%	24%	0%	74%	95%	47%	avg	752	456	494	-
										sd	27	45	10	-
9/14/2003	0%	24%	60%	70%	24%	1%	74%	88%	42%	avg	768	468	493	502
										sd	43	40	12	7

* For the reference rooms, exceeding 700 lux does not constitute improper control since the static windows admit proportional daylight.
** For all rooms, non-provision of adequate lighting indicates improper control.
Tv.diff is defined as the % difference between the command and measured visible transmittance value.

4.4. Lighting energy use and demand savings

Daily lighting energy use savings with and without the ASHRAE occupancy schedule were computed for the 12-h period from 6:00-18:00 (Table 6). Lighting demand was computed without the occupancy schedule (Table 6). The savings for a south-facing EC window (T_v=0.05-0.60) and daylight-controlled lighting system under clear and partly conditions near the autumnal equinox were as follows:

- Daily lighting energy use savings were 47.2-79.2 Wh/m^2-floor (44-59%) if the EC window and lighting system was used instead of a reference 15%-window (T_v=0.15) with the same lighting control system. Savings with occupancy were 33.4-58.2 Wh/m^2-floor (46-68%). The EC window was able to admit more daylight than the reference window for all times of the day due to its greater T_v.
- Daily lighting energy use savings were 4.0-26.8 Wh/m^2-floor (8-23%) if the EC window and lighting system was used instead of a reference 50%-window (T_v=0.50) with the same dimming lighting control system. Savings with occupancy were –0.2 to 19.1 Wh/m^2-floor (–1 to 23%). The EC window was able to admit more daylight than the reference window for all times of the day due to its greater T_v. Note that on clear sunny days, lighting energy savings occurred during the early morning and late afternoon hours (5:00-8:00 and 16:30-19:00) so schedules of occupancy should be considered.
- Daily lighting energy use savings were 89.5-136.7 Wh/m^2-floor (50-76%) if the EC window and lighting system was used instead of either reference window with no dimming lighting controls. Savings with occupancy were 69.9-107.1 Wh/m^2-floor (52-80%).
- Lighting peak demand reductions during the noon hour on a clear sunny day was 0.1-0.0 W/m^2-floor (0-3%) if the EC window and lighting system was used instead of either reference window with dimming lighting controls (September 11, 2003). Since the average work plane illuminance during the noon hour vacillated around the 510 lux setpoint with the reference 15%-window, there was a large variation in demand savings. For example, on September 11 the reference lighting control system predicted that the illuminance setpoint was met over the noon hour so the lights were set to minimum power. Demand savings was 3% on this day. On September 1, the reference lighting control system predicted that the illuminance setpoint was not met by 10-50 lux so lighting power use was at 28% of full power. Demand savings was 51% in this case.

- Lighting peak demand reductions during the noon hour on a clear sunny day was 12.6 W/m^2-floor (84%) if the EC window and lighting system was used instead of either reference window with no dimming lighting controls.

Table 6

Daily lighting energy and demand savings (per square meter floor area)

Date		---Savings:			---% Savings:		
Case (Tv):		0.15	0.50	no dayltg	0.15	0.50	no dayltg
Energy savings (Wh/m^2) with no occupancy schedule							
8/30/2003	Partly cloudy	73.7	7.3	117.0	54%	10%	65%
8/31/2003	~Clear	68.6	4.0	133.6	59%	8%	74%
9/1/2003	Clear	79.2	8.9	136.7	64%	17%	76%
9/2/2003	~Clear	66.0	4.3	133.1	58%	8%	74%
9/9/2003	Cloudy	70.7	26.8	89.5	44%	23%	50%
9/11/2003	Clear	62.3	14.1	132.6	57%	23%	74%
9/14/2003	Partly cloudy	47.2	6.6	124.1	46%	11%	69%
Energy savings (Wh/m^2) with occupancy schedule							
8/30/2003	Partly cloudy	58.2	3.5	97.4	62%	9%	73%
8/31/2003	~Clear	49.4	0.4	106.2	64%	1%	79%
9/1/2003	Clear	56.9	2.3	107.1	68%	8%	80%
9/2/2003	~Clear	46.5	-0.2	105.1	62%	-1%	79%
9/9/2003	Cloudy	54.0	19.1	69.9	46%	23%	52%
9/11/2003	Clear	45.4	6.2	106.3	62%	18%	79%
9/14/2003	Partly cloudy	33.4	0.9	100.6	50%	3%	75%
Peak demand (W/m^2) with no occupancy schedule							
8/30/2003	Partly cloudy	3.7	0.0	12.5	60%	0%	83%
8/31/2003	~Clear	2.6	0.0	12.6	52%	1%	84%
9/1/2003	Clear	2.5	0.0	12.6	51%	1%	84%
9/2/2003	~Clear	0.4	-0.7	11.9	12%	-31%	79%
9/9/2003	Cloudy	2.7	4.8	5.2	21%	33%	35%
9/11/2003	Clear	0.1	0.0	12.6	3%	0%	84%
9/14/2003	Partly cloudy	0.1	0.0	12.6	3%	0%	84%

5. Discussion

Rauh [7] classified electrochromic devices where 1) battery-like configurations with a) polymer/gel electrolytes or b) all thin film coatings have an extended open circuit memory, while 2) solution and hybrid self-erasing electrochromics with liquid or gel electrolytes require continuous current to maintain the device in the colored state. The dynamic electrochromic windows used in this field study did not fall into this classification system: the manufacturer stated that their product is an all thin-film ceramic device but requires a small trickle charge to hold it in a tinted state. Reviewing the criteria set for an ideal EC window controller in Section 3.4, the following summarizes both observations and systematic analysis for this type of device and its prototype controller at an alpha-stage of development:

- With visual inspection, the EC devices had good within-pane uniformity as the device was switching. A more accurate assessment of within-pane uniformity is best done in a laboratory setting where one can make a carefully controlled measurement of absolute T_v at multiple locations across an IGU.
- The alpha controller provided by the manufacturer in this field test responded consistently at all times when prompted and was able to set the 0.365 m^2 EC window to any intermediate state (except within the deadband range) within ~1-5 min. The exterior surface of the EC IGU varied between 14-63°C (unshielded temperature reading) over the test period.
- Visual uniformity between EC IGUs was moderately acceptable during the test period, particularly given the mixed content of the outside view. All 15 EC windows were identical in size and were

minimally shaded by the exact same local obstructions (window framing). Monitored results showed that the median transmittance of the 15 EC windows was within 10% of the requested transmittance for 60-89% of the day and when there was a deviation, the average deviation was 14-20%.

- The alpha controller provided center-of-glass T_v data. Its values differed from the independent transmittance sensors but these sensors were designed to measure relative between-pane transmittance. Laboratory tests could be used to establish absolute accuracy. While it would be helpful to attain accurate T_v data, an accuracy of 10% of value may be acceptable to both avoid control hysteresis and achieve the control objectives for energy-efficiency. Further work is needed to understand the impact of such trade-offs.

The integrated window-lighting system was breadboarded and demonstrated in this full-scale test. The system was able to meet the basic objective of maintaining interior illuminance levels within a stated range for 89-99% of the day. Limited data suggests that the photoelectric control system was not unduly influenced by the color shift produced by the electrochromic windows. The daylighting control system proved to be reliable under clear, partly cloudy, and cloudy sky conditions and at various levels of window coloration.

In prior LBNL building energy simulations, estimated lighting and space conditioning energy savings were based on controlling the electrochromic window to meet a *constant* and minimum design work plane illuminance level of 540 lux. Other EC control algorithms based on incident solar radiation or other parameters were found to yield less total energy savings for U.S. commercial buildings with an electricity-to-gas fuel ratio of 3:1. The DOE-2.1E building energy simulation program modeled this control algorithm by predicting the hourly interior daylight work plane illuminance level, then dimming the electric lighting system proportionally. The control system in this field study diverged from this simulation method. The field study system controlled the EC windows to within a design illuminance *range* of 540-700 lux rather than a constant setpoint. Restricting this design range to 540-600 lux, for example (while still maintaining the minimum desired illuminance level), will produce greater cooling energy savings but will also increase the frequency of EC switching.

Frequent switching commands to achieve tighter cooling load control can have a negative effect on how well the transmittance of side-by-side EC windows are matched since it can put the EC in a transitioning state throughout the day. The window controller was designed to meet the requested transmittance value to within ±10% once the EC has completed its switching. The EC can take 1-5 min to "complete" its switching depending on the temperature of the device and the requested percentage change in transmittance. So while in transition, the EC window's transmittance can significantly deviate from the requested transmittance resulting in a non-uniform appearance to the window wall. In this field study, although the control interval was set to every 1 min, a change in EC transmittance was not always implemented every 1 min. The alpha window controller imposed a restriction where transmittance requests that were less than 2% of the previous value were ignored. The window-lighting control system also allowed interior light levels to drift up to the maximum allowable illuminance of 700 lux before the EC was switched. Separately, implementing tighter control on the electric lighting system (and window system) is hindered by the imprecise relationship between the photosensor and predicted daylight illuminance. This issue is fundamental to conventional daylighting control systems and cannot be circumvented unless smarter algorithms are implemented. Further tests are required to better understand whether tighter cooling load control can be accomplished with acceptable window appearance.

The reported lighting energy savings must be qualified. Data are reported for unshaded south-facing windows with differing vision and frame areas between the test and reference rooms. The EC test room had 0.59 m^2 (11%) more vision area but 0.30 m^2 (11%) more framing area than the reference rooms. The spandrel area made up the remaining difference. The vision area below desk height was greater in the EC test room so these between room differences may have minimal impact on the overall lighting energy use. The lighting energy savings are given relative to an unshaded window and are therefore more theoretical than practical since visual comfort is not addressed in any of the test cases. For example, lighting and heating energy savings may be greater and cooling energy savings may be less if the unshaded EC window is compared to a reference shaded window. Additional field studies are in progress to quantify these trade-offs. At this stage in the test program, the three test rooms were configured without furniture or significant exterior obstructions, so interior illuminance levels were greater than that of typical commercial work environments. However, the 3.34-m ceiling height and less efficient pendant indirect-direct lighting system (selected for improved workplace lighting quality) lead to a slightly less efficacious lighting system than that with a typical lower ceiling (2.73 m high) and recessed lights. The window-lighting control algorithm implemented in this field test does not control direct sun or glare. Future studies are in progress that will incorporate these algorithms.

6. Conclusions

A preliminary field study was conducted that demonstrated the performance of an integrated electrochromic window-lighting system in a full-scale office testbed. The testbed consists of three identical side-by-side unfurnished offices with large area windows facing due south with minimal exterior obstructions and indirect pendant dimmable lighting fixtures. Two types of unshaded reference windows (T_v=0.50 or T_v=0.15) were used in each of the test rooms. The third room was fitted with an electrochromic window that was switched continuously over a range of T_v=0.05-0.60 using an alpha version of an EC current-to-voltage window controller. The EC window was switched to maintain the daylight work plane illuminance between 540-700 lux. In all three rooms, the fluorescent lighting was modulated to maintain a minimum work plane illuminance of 510 lux if there was sufficient daylight. This control algorithm is approximately the same used by LBNL in prior DOE-2 building energy simulation studies (maintain constant daylight levels at 540 lux) for commercial buildings.

For a south-facing large-area window with minimal exterior horizon obstructions, daily lighting energy use savings (between 6:00-18:00) were 44-59% if EC windows were used instead 15%-windows or 8-23% if EC windows were used instead of 50%-windows. The EC window yielded peak lighting demand reductions of 0-3% on a clear day compared to either reference window type with the same daylighting controls. Lighting energy and demand savings were significantly greater if the reference case had no daylighting controls as is the case with typical designs today. Savings would be less if occupancy-based control of the lighting system is taken into account. These data are given for the autumnal equinox at a latitude of 37°N. Other periods will be monitored in future work.

The integrated EC window-lighting system controller performed according to specifications: work plane illuminance levels were maintained within ±10% of the stated range for 89-99% of the day. The EC alpha window control system provided moderately acceptable accuracy in meeting a stated command transmittance level and matching transmittance between adjacent window panes. Frequent switching commands caused hysteresis with EC control and slight non-uniformity in the appearance of the window wall, since transmittance control was not as accurate when the EC was in transition. Tightening the design illuminance range and increasing the frequency of switching would improve total energy performance, but may compromise visual appearance. Further research is needed to improve EC controller accuracy. Separately, the spectral shift caused by the EC window switching from clear to a dark blue does not appear to significantly skew the photosensor response to interior daylight levels. This bodes well for daylighting control applications, although more comprehensive tests are warranted. Future tests are planned to evaluate alternate control strategies that address both energy and non-energy issues. Each of these control strategies ultimately involves human factors input that may increase or decrease measured savings. In later phases of the field measurement program, we will study these as well as other human factors issues in conjunction with the engineering data.

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